METHOD AND SYSTEM FOR ADAPTIVE
5
CHANNEL ESTIMATION TECHNIQUES

FIELD OF THE INVENTION

In general, the invention relates to wireless communication systems. More specifically, the invention relates to cellular communications and in

10 particular, to a method and system for channel estimation within cellular communications.

BACKGROUND OF THE INVENTION

For optimal reception of a digital signal over a broadband cellular channel, the channel to a desired transmitter must be determined. Because

15 channels can consist of a number of multipath components or rays each with its own time of arrival and Doppler frequency, a channel estimator should determine the actual time of arrivals (TOA's), Doppler frequencies, and their corresponding complex gains. The channel estimator should also adapt to many different transmitting environments where there are a very large number

20 of rays with a TOA spread and a Doppler frequency spread. A maximum likelihood (ML) channel estimation approach as is known in the art, may provide the best TOA and Doppler frequency estimates, however it lacks a closed form solution.

Prior art TOA estimators such as a TOA estimation using ESPRIT, are

25 not robust to channel conditions with a large number of rays with a TOA spread and are not suitable for multi-user channel estimation. Other channel estimators may assume a worst-case channel and thus need to estimate many more parameters than is necessary under typical channel conditions.

Thus, there is a significant need for a method and device for improving

30 multi-user channel estimation techniques that overcome the above disadvantages and shortcomings, as well as other disadvantages.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is an overview diagram of a preferred embodiment for a cellular communication system in accordance with the present invention;

5 **FIG. 2** is a block diagram illustration of a communication device for the cellular communication system in **FIG. 1**, in accordance with the present invention;

FIG. 3 is a block diagram illustrating details of a channel estimation device for the communication device of **FIG. 2**, in accordance with the present

10 invention;

FIG. 4 is a flow chart representation of a method performed by one embodiment of the Channel Estimation Device of **FIG. 3**, in accordance with the present invention;

FIG. 5 is a flow chart representation of a method performed by a

15 second embodiment of the Channel Estimation Device of **FIG. 3**, in accordance with the present invention;

FIG. 6 is a flow chart representation of a method performed by a third embodiment of the Channel Estimation Device of **FIG. 3**, in accordance with the present invention; and

20 **FIG. 7** is a flow chart representation of a method performed by a fourth embodiment of the Channel Estimation Device of **FIG. 3**, in accordance with the present invention.

DETAILED DESCRIPTION OF A PREFERRED EMBODIMENT

FIG. 1 illustrates a wireless communication system **100** in accordance

25 with one embodiment of the present invention. As shown in **FIG. 1**, a base station **110** provides communication service to a geographic region known as a cell **103**. At least one user device **120** and **130** communicate with the base station **110**.

As shown in **FIG. 1**, user devices **120** have a single antenna **101**, while user devices **130** have at least one antenna **101**. One embodiment of the invention provides that the user devices **120** and **130**, as well as the base

5   station **110** may transmit, receive, or both from the at least one antenna **101**. An example of this would be a typical cellular telephone. Additionally, one embodiment of the invention may provide that the communication system **100** uses techniques such as orthogonal frequency division multiplexing (OFDM). Furthermore, one embodiment may provide that alternative transmitters and

10   receivers known in the art may be used and user devices as well as base stations may be interchanged and referred to commonly as communication devices, transmitting units, receiving units, transmitters, receivers, transceivers, cell phones, or any like term known in the art.

Illustrated in **FIG. 2** is a block diagram for one embodiment of a

15   communication device **200** that may be used within the wireless communication system. The communication device **200** may include at least one antenna **101** wherein the outputs of the antenna may be provided to a receiving unit **201**. The outputs of the receiving unit **201** may be provided to at least one antenna combiner **202**. The antenna combiner **202** may process

20   multiple signals into one signal. The signals from the receiving units **201** may also be fed into a combiner controller **210**, which can regulate the operation of the at least one antenna combiner **202**. The signals from the receiving units **201** may also be fed into a channel estimation device **208**. A pilot symbol generator **212** capable of generating pilot symbol information may be used by

25   the combiner controller **210** to control the antenna combiner **202**. The pilot symbol information generated by the pilot symbol generator **212** can also be used by the channel estimation device **208** to estimate the channel responses between a transmitting device and the communication device **200**. The output of the antenna combiner **202** may be fed into an information decoding unit

30   **206**, which can decode an antenna combiner output **204** and generate data information **213** that was received by the antennas **101**.

A channel estimation device **300** suitable for use in one embodiment of the communication device is illustrated within **FIG. 3**. One embodiment of the channel estimation device **300** may include a received training memory unit

5 **310**, capable of storing output signals from a receiving unit. A microprocessor **340** may collect the pilot sequence information from a pilot sequence input **350** and may receive inputs from a TOA matrices memory unit **320**. The received data stored in the received training memory unit **310,** and the inputs from the microprocessor **340** may be fed into a matrix multiplier **330** where

10 they are multiplied. The result can be used in iteration calculations to compute a channel estimate in one embodiment of the invention. In another embodiment of the invention, the TOA matrices memory unit **320**, the matrix multiplier **330**, and the microprocessor **340** may be implemented in a processor **380**. Additionally, an embodiment of the invention may provide the

15 microprocessor **340** to make use of a Fast Fourier Transform device **390** to efficiently implement the channel estimation algorithms of the invention.

FIG. 4 is an illustration of a block diagram for a frequency-domain multi-user channel estimation method **400** in accordance with the invention. In order to describe the method of frequency-domain multi-user channel

20 estimation **400**, multi-user channel estimation based on time of arrivals (TOAs) for multi-path components of a transmitted signal will first be described.

Using prior art TOA estimators such as estimation of signal parameters via rotational invariance techniques (ESPRIT), TOA's for use in OFDM

25 channel estimation may be found; however, ESPRIT fails when there are many multipath arrival times, or when the communication system is multi-user. In addition, ESPRIT is not an optimal TOA estimator since it is not a maximum likelihood (ML) estimator. The performance of ESPRIT may also suffer when the pilot symbols are not constant modulus. This can occur when

30 the received signals need to be divided by the pilot symbols, which can result in an emphasis on subcarriers where the pilot is weaker in power.

In one embodiment of the invention, a near-ML technique for multiple sinusoidal estimation may be extended to a multiple user TOA/channel estimation in OFDM or for any frequency-domain channel. The received

5   OFDM signal in the frequency-domain may be given as:

$$(M \times 1) \quad \mathbf{Y}(k) = \sum_{u=1}^{U} \mathbf{H}_u(k) x_u(k) + \mathbf{N}(k) \tag{1}$$

where M is the number of receive antennas, U is the number of users or transmitters, $\mathbf{H}_u(k)$ (an $M \times 1$ vector) is user u's channel on subcarrier k, $x_u(k)$ is user u's symbol on subcarrier k, and $\mathbf{N}(k)$ is a vector of additive noise that

10   may have covariance matrix $\sigma_n^2 \mathbf{I}$ where σ_n^2 is the noise power. The dependence on time (or baud number) has been removed to simplify the detailed description. User u's channel on antenna m may be modeled by the equation:

$$H_{m,u}(k) = \mathbf{f}_u^H(k) \gamma_{m,u} \tag{2}$$

15   where the $P_u \times 1$ vector, $\gamma_{m,u}$, is user u's channel gains on antenna m, P_u is the number of distinct TOA estimates for user u, and the $P_u \times 1$ vector $\mathbf{f}_u(k)$ may be represented by the equation:

$$\mathbf{f}_u(k) = \begin{bmatrix} e^{jt_{u,1}k} \\ \vdots \\ e^{jt_{u,P_u}k} \end{bmatrix} \tag{3}$$

In equation (3), $t_{u,\ell}$ is the scaled TOA (i.e., not the actual TOA) for user u and

20   path ℓ ($\ell=1,\ldots,P_u$). The true TOA's can be recovered by multiplying $t_{u,\ell}$ by $K/(2\pi W)$ where W is the bandwidth of the K subcarriers.

For one embodiment of the invention, equation (2) is essentially a sum of weighted sinusoids. The sinusoidal frequencies of equation (2) (which correspond to the TOA's) and their relative gains need to be determined to

25   establish the channel estimation. Also, the TOA's corresponding to a single user may be assumed to be the same across the receive antennas. If hardware implementations cause the synchronization to be different on each

receive antenna or cause the delay to be different due to filtering effects, then the TOA estimator may need to be run separately on each receive antenna.

Stacking the received frequency-domain signal on antenna m across K subcarriers may be expressed as:

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$$(K \times 1) \quad \mathbf{Y}_m = \begin{bmatrix} Y_m(0) \\ \vdots \\ Y_m(K-1) \end{bmatrix} = \sum_{u=1}^{U} \mathbf{X}_u \mathbf{F}_u \boldsymbol{\gamma}_{m,u} + \mathbf{N}_m \qquad (4)$$

where $K \times K$ $\mathbf{X}_u$ and $K \times P_u$ $\mathbf{F}_u$ are:

$$\mathbf{X}_u = \operatorname{diag}\{x_u(0), \ldots, x_u(K-1)\} \quad \text{and} \quad \mathbf{F}_u = \begin{bmatrix} \mathbf{f}_u^H(0) \\ \vdots \\ \mathbf{f}_u^H(K-1) \end{bmatrix}. \qquad (5)$$

Within another embodiment of the invention, the goal of channel estimation may be to find for each user the number of TOA's, P_u, the TOA's themselves,

10 $t_{u,\ell}$, and their gain values, $\gamma_{m,\ell}$. A multi-dimensional search over all of these unknown parameters to find the best fit according to (4) may be a prohibitively complex task. Therefore the problem can be separated into two more tractable problems where the gains can be eliminated from the estimation problem and then a search can be performed just over the number of TOA's

15 and the TOA's themselves. To determine the gains, a Least Squares (LS) approach may be taken with a weighting, α, placed on the magnitudes of $\gamma_{m,\ell}$ so that the inverse in the following equation (7) is not ill conditioned. For the following equation (6), when $\alpha=0$ the solution is the ML estimator. The previously described parameters may be found as the solution to the

20 equation:

$$\min_{t_\ell, P_u, \gamma_{m,u}} \sum_{m=1}^{M} \left| \mathbf{Y}_m - \sum_{u=1}^{U} \mathbf{X}_u \mathbf{F}_u \boldsymbol{\gamma}_{m,u} \right|^2 + \alpha \sum_{m=1}^{M} \sum_{u=1}^{U} \boldsymbol{\gamma}_{m,u}^H \boldsymbol{\gamma}_{m,u} \qquad (6)$$

The solution of (6) for the magnitude vectors, $\gamma_{m,\ell}$, given the TOA estimates can be shown to be:

$$(P \times 1) \quad \boldsymbol{\gamma}_m = \begin{bmatrix} \gamma_{m,1} \\ \vdots \\ \gamma_{m,U} \end{bmatrix} = \mathbf{R}^{-1} \mathbf{H}_m \qquad (7)$$

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where $P = \sum_{u=1}^{U} P_u$, and $P{\times}P$ **R** and $P{\times}1$ **H**$_m$ are given as:

$$\mathbf{R} = \begin{bmatrix} \mathbf{R}_{1,1} & \cdots & \mathbf{R}_{1,U} \\ \vdots & \ddots & \vdots \\ \mathbf{R}_{1,U}^H & \cdots & \mathbf{R}_{U,U} \end{bmatrix} \quad \text{and} \quad \mathbf{H}_m = \begin{bmatrix} \mathbf{F}_1^H \mathbf{X}_1^H \mathbf{Y}_m \\ \vdots \\ \mathbf{F}_U^H \mathbf{X}_U^H \mathbf{Y}_m \end{bmatrix} \quad (8)$$

and $P_u{\times}P_v$ **R**$_{u,v}$ is given as:

$$\mathbf{R}_{u,v} = \mathbf{F}_u^H \mathbf{X}_u^H \mathbf{X}_v \mathbf{F}_v + \alpha \delta(u-v) \mathbf{I}_{P_u \times P_v} \quad (9)$$

5   where $\mathbf{I}_{n \times m}$ is an $n{\times}m$ matrix of all zeros except the upper left

min(n,m)×min(n,m) corner which is an identity matrix of size

min(n,m)×min(n,m) and $\delta(n)$=1 when n=0 and $\delta(n)$=0 when $n{\neq}0$.

The mean squared error of the channel estimator can be shown to be:

$$E = \sum_{m=1}^{M} |\mathbf{Y}_m|^2 - \sum_{m=1}^{M} \mathbf{H}_m^H \mathbf{R}^{-1} \mathbf{H}_m \quad (10)$$

10   The error does not depend on $\gamma_{m,\ell}$ and thus the TOA's can be searched

independently of the gain values. This leads to the near-ML TOA search

described below. At each step in the algorithm, a two-dimensional search

may be performed to find an additional TOA and the user to which it belongs

so that the MSE in equation (10) can be minimized. Because only a single

15   TOA is added during an iteration of equation (10), $\mathbf{R}^{-1}$ may be updated at each

step by using the rank one inverse update formula (the rank one inverse

update formula is known in the art). By only adding a single user's TOA at

each step, the algorithm can accommodate the case of each user having a

different number of TOA's.

20   The following is the near-ML multi-user TOA search, and [] is used to

represent an empty matrix. First, let $K{\times}1$ **G**$_{u,m}$ and $K{\times}1$ **z**$_u(t)$ be:

$$\mathbf{G}_{u,m} = \mathbf{X}_u^H \mathbf{Y}_m \quad \text{and} \quad \mathbf{z}_u(t) = \begin{bmatrix} 1 \\ e^{-jt} \\ \vdots \\ e^{-j(K-1)t} \end{bmatrix} \quad (11)$$

1. $E_0 = \sum_{m=1}^{M} |\mathbf{Y}_m|^2$, $\ell=0$, $\mathbf{R}_0^{-1} = []$, $r_0=[]$, $F_0=[]$, $H_0=[]$, $q_0=[]$, and

$$d_u = \alpha + \sum_{\ell=0}^{K-1} |x_u(k)|^2 \text{ for } u=1,\ldots,U.$$

2. $\ell=\ell+1$, $(\ell-1)\times 1$ $\mathbf{r}_\ell = \mathbf{F}_{\ell-1}^H \mathbf{X}_{u_\ell} \mathbf{z}_{u_\ell}(t_\ell)$, $E_\ell = E_{\ell-1} - \dfrac{\sum_{m=1}^{M} \mathbf{q}_{\ell,m}^H \mathbf{q}_{\ell,m}}{d_{u_\ell} - \mathbf{r}_\ell^H \mathbf{R}_{\ell-1}^{-1} \mathbf{r}_\ell}$

where $(\ell \times 1)$ $\mathbf{q}_{\ell,m} = \begin{bmatrix} -\mathbf{H}_{m,\ell-1}^H \mathbf{R}_{\ell-1}^{-1} \mathbf{r}_\ell \\ \mathbf{G}_{u,m}^H \mathbf{z}_{u_\ell}(t_\ell) \end{bmatrix}$. Perform a two dimensional search over t_ℓ

5 and u_ℓ (u_ℓ is which user's TOA minimizes E_ℓ) and find the t_ℓ and u_ℓ to minimize

E_ℓ and then update:

$(\ell \times 1)$ $\mathbf{H}_{m,\ell} = \begin{bmatrix} \mathbf{H}_{m,\ell-1} \\ \mathbf{z}_{u_\ell}^H(t_\ell)\mathbf{G}_{u_\ell,m} \end{bmatrix}$, $\mathbf{F}_\ell = [\mathbf{F}_{\ell-1} \mid \mathbf{X}_u \mathbf{z}_{u_\ell}(t_\ell)]$, and

$$\mathbf{R}_\ell^{-1} = \begin{bmatrix} \mathbf{R}_{\ell-1}^{-1} & \mathbf{0} \\ \mathbf{0}^T & 0 \end{bmatrix} + \dfrac{\begin{bmatrix} -\mathbf{R}_{\ell-1}^{-1}\mathbf{r}_\ell \\ 1 \end{bmatrix} \begin{bmatrix} -\mathbf{r}_\ell^H \mathbf{R}_{\ell-1}^{-1} & 1 \end{bmatrix}}{d_{u_\ell} - \mathbf{r}_\ell^H \mathbf{R}_{\ell-1}^{-1} \mathbf{r}_\ell}.$$

3. If stop criteria as described below is not reached then go back to

10 step 2.

4. The total number of TOA's, P, is ℓ, the TOA's are t_1 through t_ℓ,

and the users associated with each TOA are u_1 through u_ℓ. For one

embodiment of the invention, the search over TOA's, t_ℓ, performed in step 2

15 may be done over some finite set of times from t_{min} to t_{max}. Since there are a

finite number of TOA's to search over, $\mathbf{r}_\ell$ and $\mathbf{G}_{u,m}^H \mathbf{z}_{u_\ell}(t_\ell)$ can be pre-

computed.

In one embodiment of the invention, the stopping criteria may be to

stop when the error at step ℓ, E_ℓ, is close to the noise floor. This embodiment

20 of course, requires an estimate of the noise power. Another embodiment of

the invention may define the stopping criteria as "stop if the value of the Peak

to Average Power Ratio (PAPR) of the error update at step ℓ versus all of the

TOA's being searched is less than some predetermined threshold". The error update at step ℓ may be expressed as the equation $e_\ell = \dfrac{\sum_{m=1}^{M} \mathbf{q}_{\ell,m}^H \mathbf{q}_{\ell,m}}{d_{u_\ell} - \mathbf{r}_\ell^H \mathbf{R}_{\ell-1}^{-1} \mathbf{r}_\ell}$.

An example of a preferred embodiment may set the predetermined threshold to five. The PAPR stop criteria can provide a value for σ_n^2 by

5   dividing E_ℓ by MK. An example of this is the mean squared error averaged over all M antennas and all K subcarriers. Additionally, once the TOA's are found, the channel gains, γ_m, can be found using equation (7).

One embodiment of the invention may extend the previous algorithm to both TOA and Doppler frequency estimation. The received OFDM signal in

10   the frequency-domain may be expressed as the equation:

$$(M \times 1) \quad \mathbf{Y}(k,b) = \sum_{u=1}^{U} \mathbf{H}_u(k,b) x_u(k,b) + \mathbf{N}(k,b) \qquad (12)$$

where M is the number of receive antennas, U is the number of users or transmitters, $\mathbf{H}_u(k,b)$ is user u's channel on subcarrier k on baud number b,

15    $x_u(k,b)$ is user u's symbol on subcarrier k and baud b, and $\mathbf{N}(k,b)$ is a vector of additive noise with covariance matrix $\sigma_n^2 \mathbf{I}$. User u's channel on antenna m may be modeled by the equation:

$$H_{m,u}(k,b) = \mathbf{f}_u^H(k,b)\gamma_{m,u} \qquad (13)$$

where $P_u \times 1$ $\gamma_{m,u}$ is user u's channel gains on antenna m, P_u is the number of

20   TOA and Doppler frequency estimates for user u, and $P_u \times 1$ $\mathbf{f}_u(k,b)$ may be expressed as:

$$\mathbf{f}_u(k,b) = \begin{bmatrix} e^{j(t_{u,1}k - f_{u,1}b)} \\ \vdots \\ e^{j(t_{u,P_u}k - f_{u,P_u}b)} \end{bmatrix} \qquad (14)$$

where $t_{u,\ell}$ and $f_{u,\ell}$ in (14) are the scaled TOA and Doppler frequency respectively, for user u and path ℓ ($1 \leq \ell \leq P_u$). Within one embodiment of the

25   invention, the true TOA's can be recovered by multiplying $t_{u,\ell}$ by $K/(2\pi W)$

where W is the bandwidth of the K subcarriers. Additionally, the true Doppler frequencies can be recovered by dividing $f_{u,\ell}$ by $2\pi\Delta N_s$ where Δ is the time between OFDM time-domain samples and N_s is the number of time samples between two adjacent OFDM bauds such as the number of samples between

5   bauds b and $b+1$.

For a fixed b, equation (13) is essentially a sum of weighted sinusoids just like the TOA-only embodiment. For channel estimation within another embodiment, the sinusoidal frequencies across frequency (these correspond to the TOA's), the sinusoidal frequencies across time (these correspond to the

10   Doppler frequencies), and their relative gains may need to be determined. Further, the TOA's and Doppler frequencies may be assumed to be the same across the receive antennas for a single user. If hardware implementations cause the synchronization to be different on each receive antenna, cause the delay to be different due to filtering effects, or cause the frequency offsets to

15   be different, then the TOA/Doppler frequency estimator may need to be run separately on each receive antenna.

Another embodiment of the invention may assume that there are B bauds containing all known pilots on all K subcarriers. The extension to arbitrary pilot formats is straightforward to anyone trained in the art. Stacking

20   the received frequency-domain signal on antenna m across K subcarriers and B pilot bauds gives the following equation:

$$(KB \times 1) \quad \mathbf{Y}_m = \begin{bmatrix} Y_m(0,0) \\ \vdots \\ Y_m(K-1,0) \\ Y_m(0,1) \\ \vdots \\ Y_m(K-1,B-1) \end{bmatrix} = \sum_{u=1}^{U} \mathbf{X}_u \mathbf{F}_u \gamma_{m,u} + \mathbf{N}_m \qquad (15)$$

where $BK \times BK$ $\mathbf{X}_u$ and $BK \times P_u$ $\mathbf{F}_u$ are:

$$\mathbf{X}_u = \text{diag}\{x_u(0,0),\ldots,x_u(K-1,0),x_u(0,1),\ldots,x_u(K-1,B-1)\}$$

$$\text{and} \quad \mathbf{F}_u = \begin{bmatrix} \mathbf{f}_u^H(0,0) \\ \vdots \\ \mathbf{f}_u^H(K-1,0) \\ \mathbf{f}_u^H(0,1) \\ \vdots \\ \mathbf{f}_u^H(K-1,B-1) \end{bmatrix} \tag{16}$$

For one embodiment of the invention, the goal of channel estimation may be to find for each user the number of TOA's/Doppler frequencies, P_u, the TOA's and Doppler frequencies themselves, $t_{u,\ell}$ and $f_{u,\ell}$, and their gain values, $\gamma_{m,\ell}$. To determine the gains, a Least Squares (LS) approach may be taken with a weighting, α, placed on the magnitudes of $\gamma_{m,\ell}$ so that the inverse in the following equation (18) is not ill conditioned. It is obvious that when $\alpha=0$ the solution to the following equation (17) is the ML estimator. The parameters are found as the solution to:

$$\min_{t_\ell, f_\ell, P_u, \gamma_{m,u}} \sum_{m=1}^{M} \left| \mathbf{Y}_m - \sum_{u=1}^{U} \mathbf{X}_u \mathbf{F}_u \gamma_{m,u} \right|^2 + \alpha \sum_{m=1}^{M} \sum_{u=1}^{U} \gamma_{m,u}^H \gamma_{m,u} \tag{17}$$

The solution of equation (17) for the magnitude vectors, $\gamma_{m,\ell}$, given the TOA and Doppler frequency estimates can be shown to be:

$$(P \times 1) \quad \gamma_m = \begin{bmatrix} \gamma_{m,1} \\ \vdots \\ \gamma_{m,U} \end{bmatrix} = \mathbf{R}^{-1} \mathbf{H}_m \tag{18}$$

where $P = \sum_{u=1}^{U} P_u$, and $P \times P$ $\mathbf{R}$ and $P \times 1$ $\mathbf{H}_m$ are given as:

$$\mathbf{R} = \begin{bmatrix} \mathbf{R}_{1,1} & \cdots & \mathbf{R}_{1,U} \\ \vdots & \ddots & \vdots \\ \mathbf{R}_{1,U}^H & \cdots & \mathbf{R}_{U,U} \end{bmatrix} \quad \text{and} \quad \mathbf{H}_m = \begin{bmatrix} \mathbf{F}_1^H \mathbf{X}_1^H \mathbf{Y}_m \\ \vdots \\ \mathbf{F}_U^H \mathbf{X}_U^H \mathbf{Y}_m \end{bmatrix} \tag{19}$$

and $P_u \times P_v$ $\mathbf{R}_{u,v}$ is given as:

$$\mathbf{R}_{u,v} = \mathbf{F}_u^H \mathbf{X}_u^H \mathbf{X}_v \mathbf{F}_v + \alpha \delta(u-v) \mathbf{I}_{P_u} \tag{20}$$

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The mean squared error (MSE) of the channel estimator can be shown to be:

$$E = \sum_{m=1}^{M} |Y_m|^2 - \sum_{m=1}^{M} H_m^H R^{-1} H_m \qquad (21)$$

In one embodiment of the invention, the error may not depend on $\gamma_{m,\ell}$ and thus the TOA's and Doppler frequencies can be searched independently

5   of the gain values. This leads to a near-ML TOA/Doppler frequency search. At each step in the algorithm, a three-dimensional search may be performed to find an additional TOA, an additional Doppler frequency, and the user to which they belong so that the MSE in equation (21) is minimized. Because only a single TOA/Doppler frequency pair is added during an iteration of

10   equation (21), R^{-1} can be updated at each step by using the rank one inverse update formula, as is known in the art. By only adding a single user's TOA/Doppler frequency pair at each step, the algorithm can accommodate an embodiment of the invention where each user may have a different number of TOA's and Doppler frequencies. The following procedure may provide the

15   near-ML multi-user TOA/Doppler frequency search, where [] is used to represent an empty matrix. First, let $BK \times 1$ $G_{u,m}$ and $BK \times 1$ $z_u(t,f)$ be:

$$G'_{u,m} = X_u^H Y_m \quad \text{and} \quad z_u(t,f) = \begin{bmatrix} e^{-j(0t-0f)} \\ \vdots \\ e^{-j((K-1)t-0f)} \\ e^{-j(0t-f)} \\ \vdots \\ e^{-j((K-1)t-(B-1)f)} \end{bmatrix} \qquad (22)$$

1. $E_0 = \sum_{m=1}^{M} |Y_m|^2$, $\ell=0$, $R_0=[]$, $r_0=[]$, $F_0=[]$, $H_0=[]$, $q_0=[]$, and

$$d_u = \alpha + \sum_{b=0}^{B-1} \sum_{\ell=0}^{K-1} |x_u(k,b)|^2 \quad \text{for } u=1,\ldots,U.$$

20   2. $\ell=\ell+1$, $(\ell-1) \times 1$ $r_\ell = F_{\ell-1}^H X_{u_\ell} z_{u_\ell}(t_\ell, f_\ell)$, $E_\ell = E_{\ell-1} - \dfrac{\sum\limits_{m=1}^{M} q_{\ell,m}^H q_{\ell,m}}{d_{u_\ell} - r_\ell^H R_{\ell-1}^{-1} r_\ell}$

where $(\ell \times 1)$ $q_{\ell,m} = \begin{bmatrix} -H_{m,\ell-1}^H R_{\ell-1}^{-1} r_\ell \\ G_{u,m}^H z_{u_\ell}(t_\ell, f_\ell) \end{bmatrix}$.

Perform a three dimensional search over t_ℓ, f_ℓ, and u_ℓ (which user's TOA/Doppler frequency pair minimizes E_ℓ) and find the t_ℓ, f_ℓ, and u_ℓ to minimize E_ℓ and then update:

$$(\ell \times 1)\ \mathbf{H}_{m,\ell} = \begin{bmatrix} \mathbf{H}_{m,\ell-1} \\ \mathbf{z}_{u_\ell}^H(t_\ell, f_\ell)\mathbf{G}_{u_\ell,m} \end{bmatrix}, \quad \mathbf{F}_\ell = [\mathbf{F}_{\ell-1} \mid \mathbf{X}_u \mathbf{z}_{u_\ell}(t_\ell, f_\ell)], \text{ and}$$

$$5 \qquad \mathbf{R}_\ell^{-1} = \begin{bmatrix} \mathbf{R}_{\ell-1}^{-1} & \mathbf{0} \\ \mathbf{0}^T & 0 \end{bmatrix} + \frac{\begin{bmatrix} -\mathbf{R}_{\ell-1}^{-1}\mathbf{r}_\ell \\ 1 \end{bmatrix}\begin{bmatrix} -\mathbf{r}_\ell^H\mathbf{R}_{\ell-1}^{-1} & 1 \end{bmatrix}}{d_{u_\ell} - \mathbf{r}_\ell^H\mathbf{R}_{\ell-1}^{-1}\mathbf{r}_\ell}.$$

3.   If stop criteria as described below is not reached then go back to step 2.

4.   The total number of TOA's and Doppler frequencies P is ℓ, the

10   TOA's are t_1 through t_ℓ, the Doppler frequencies are f_1 through f_ℓ, and the users associated with each TOA are u_1 through u_ℓ.

For another embodiment of step two, the search over TOA's, t_ℓ, may be performed over some finite set of times from t_{min} to t_{max} and the search over Doppler frequencies may also be performed over a finite set of frequencies

15   from f_{min} to f_{max}. Since there are a finite number of TOA's and Doppler frequencies to search over, $\mathbf{r}_\ell$ and $\mathbf{G}_{u,m}^H \mathbf{z}_{u_\ell}(t_\ell, f_\ell)$ may be pre-computed.

One embodiment of the invention may provide for the stopping criteria to stop when the error at step ℓ, E_ℓ, is close to the noise floor. That embodiment of course, requires an estimate of the noise power. Another

20   embodiment of the invention may provide the stopping criteria to quit when the Peak to Average Power Ratio (PAPR) of the error update at step ℓ versus all of the time of arrivals and Doppler frequencies being scanned is less than some predetermined value. The error update at iteration ℓ may be expressed

as $e_\ell = \dfrac{\displaystyle\sum_{m=1}^{M}\mathbf{q}_{\ell,m}^H\mathbf{q}_{\ell,m}}{d_{u_\ell} - \mathbf{r}_\ell^H\mathbf{R}_{\ell-1}^{-1}\mathbf{r}_\ell}$. Dividing E_ℓ by MBK, a value for σ_n^2 may be obtained.

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Once the TOA's and Doppler frequencies are found, the channel gains, γ_m, can be found using equation (18).

Common among the embodiments of channel estimation methods in accordance with the present invention, is that each method adapts (is

5   adaptive) to the channel conditions, thereby using a smaller set of channel parameters than existing channel estimators. The channel conditions may include multi-path components, channel gains of multi-path components, time-taps, maximum delay spread, directions of arrivals, and/or additional channel attributes as are known in the art. The adaptivity of the invention may be in

10   part or whole, a function of channel estimation iteration, channel estimation TOA, and/or least squares channel estimation. Each method of adaptivity described within the detailed description of the invention may provide an adapted channel estimate in place of the received channel estimate thereby improving performance in most channel conditions. One such embodiment

15   refers again to **FIG. 4**, where the frequency-domain multi-user channel estimation method **400** can provide multi-user TOA and Doppler frequency near-ML estimations.

The channel estimation method **400** may be provided a noisy channel estimate for at least one user $\mathbf{G}_{u,m}$, and an update vector $z_u(t,f)$, **410** and may

20   be represented by the equation:

$$\mathbf{G}_{u,m} = \mathbf{X}_u^H \mathbf{Y}_m \quad \text{and} \quad z_u(t,f) = \begin{bmatrix} e^{-j(0t-0f)} \\ \vdots \\ e^{-j((K-1)t-0f)} \\ e^{-j(0t-f)} \\ \vdots \\ e^{-j((K-1)t-(B-1)f)} \end{bmatrix} . \text{ The iteration variables}$$

may next be initialized that may include setting the iteration number ℓ, to zero **420**. The iteration variables and how they are initialized may be represented by the equations $E_0 = \sum_{m=1}^{M} |\mathbf{Y}_m|^2$, $\ell=0$, $\mathbf{R}_0=[]$, $\mathbf{r}_0=[]$, $\mathbf{F}_0=[]$, $\mathbf{H}_0=[]$, $\mathbf{q}_0=[]$, and

25   $d_u = \alpha + \sum_{b=0}^{B-1} \sum_{\ell=0}^{K-1} |x_u(k,b)|^2$ for u=1,...,U, where [] indicates an empty matrix as is

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known in the art. After initialization, the iteration number may be incremented by one **430**. The channel estimation method **400** may then calculate an error update at the incremented iteration for all TOA values, Doppler values, and users being scanned as a function of the iteration variables and the noisy

5   channel estimates for at least one user **440**. In one embodiment of the invention the TOA's t may be scanned from t_{min} to t_{max}, the Doppler frequencies f may be scanned from f_{min} to f_{max}, and the users, u, may be scanned from one to U. The error update at iteration ℓ can be a function of TOA, Doppler frequency, and user and for this embodiment may be equated

10   as $$e_\ell(t,f,u) = \frac{\sum_{m=1}^{M} \mathbf{q}_{\ell,m}^H \mathbf{q}_{\ell,m}}{d_{u_\ell} - \mathbf{r}_\ell^H \mathbf{R}_{\ell-1}^{-1} \mathbf{r}_\ell}$$, where $(\ell-1)\times 1 \ \mathbf{r}_\ell = \mathbf{F}_{\ell-1}^H \mathbf{X}_{u_\ell} \mathbf{z}_{u_\ell}(t_\ell, f_\ell)$, and

$$(\ell \times 1) \ \mathbf{q}_{\ell,m} = \begin{bmatrix} -\mathbf{H}_{m,\ell-1}^H \mathbf{R}_{\ell-1}^{-1} \mathbf{r}_\ell \\ \mathbf{G}_{u,m}^H \mathbf{z}_{u_\ell}(t_\ell, f_\ell) \end{bmatrix}$$ Determining which t, f, and u that can maximize the error update at iteration ℓ can be performed with the determined values labeled t_ℓ, f_ℓ, and u_ℓ respectively **450**. The error at step ℓ, E_ℓ, may be updated to equate $E_\ell = E_{\ell-1} - e_\ell(t_\ell, f_\ell, u_\ell)$. Next, the following iteration variables may be

15   updated **460**: $$(\ell \times 1) \ \mathbf{H}_{m,\ell} = \begin{bmatrix} \mathbf{H}_{m,\ell-1} \\ \mathbf{z}_{u_\ell}^H(t_\ell, f_\ell)\mathbf{G}_{u_\ell,m} \end{bmatrix}$$, $\mathbf{F}_\ell = [\mathbf{F}_{\ell-1} \mid \mathbf{X}_u \mathbf{z}_{u_\ell}(t_\ell, f_\ell)]$, and

$$\mathbf{R}_\ell^{-1} = \begin{bmatrix} \mathbf{R}_{\ell-1}^{-1} & \mathbf{0} \\ \mathbf{0}^T & \mathbf{0} \end{bmatrix} + \frac{\begin{bmatrix} -\mathbf{R}_{\ell-1}^{-1} \mathbf{r}_\ell \\ 1 \end{bmatrix} \begin{bmatrix} -\mathbf{r}_\ell^H \mathbf{R}_{\ell-1}^{-1} & 1 \end{bmatrix}}{d_{u_\ell} - \mathbf{r}_\ell^H \mathbf{R}_{\ell-1}^{-1} \mathbf{r}_\ell}$$.

If the appropriate stopping criteria have been reached **470**, the channel estimation method **400** may be terminated **480**. If the appropriate stopping criteria have not been reached **470**, then the channel estimation method **400**

20   may proceed to block **430**.

In another embodiment of **FIG. 4**, directions of arrivals can be scanned in a similar manner as the TOAs and the Doppler frequencies. Anyone skilled in the art can modify the channel estimator of **FIG. 4** to scan for direction of arrivals in a near-ML sense.

25

Another embodiment of the invention illustrating an adaptive channel estimator is **FIG. 5**, where a TOA with a phase shift training channel estimation method **500** may provide channel estimation by shifting multiple

5 user channels to non-overlapped time regions. Given that a first user's pilots are $p_1(k)$, then a subsequent users' pilots (say the nth) may be determined as:

$$p_n(k) = p_1(k)e^{-j2\pi k(n-1)L_s/K} \tag{23}$$

where L_s may represent the maximum length in number of time samples of all users' channel responses. The phase shift training channel estimation

10 method **500** may begin by being provided a noisy channel estimate and a time separation value **510**. The time separation value L_s may be at least as long as the expected delay in sample times. The noisy channel estimate may be equated as $H_n(k) = Y(k)/p_1(k)$. The TOA's may be estimated next **520** from the noisy channel estimate using any existing TOA estimator known in the art.

15 The use of the training in (23) may turn the multi-user TOA estimation problem stated previously in equation (6) to a single-user equivalent problem where a user u's TOA's can be from $(u-1)L_s\Delta N/K$ to $uL_s\Delta N/K$, and Δ may be the time between OFDM time-domain samples. The complexity is similar to the multi-user embodiment of **FIG. 4** because the number of TOA's that need

20 to be searched at each iteration using the phase shift training may be the same as before. Thus, the final step of the phase shift training channel estimation method **500** may be to separate the TOA's for each user given what time band they are in **530**. For one embodiment of the invention, user u's TOAs are from $(u-1)L_s\Delta N/K$ to $uL_s\Delta N/K$. The phase shift training can

25 enable the use of ESPRIT as a multi-user TOA estimator because the phase shift training problem can turn the multi-user TOA search into a single-user equivalent.

In another embodiment of the invention, a gradient search may be performed to improve the TOA estimates from any existing TOA estimator.

30 This embodiment may provide that for a single user, the TOA estimation can be expressed as follows if the number of TOA's, P, is known:

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$$\min_{t_\ell, \gamma_\ell} \sum_{k=0}^{K-1} \left| \sum_{\ell=1}^{P} \gamma_\ell e^{-jkt_\ell} - \mathbf{H}_n(k) \right|^2 \qquad (24)$$

where the ($M\times1$) noisy channel estimate $H_n(k)$ is $\mathbf{H}_n(k) = \mathbf{Y}(k)/x(k)$ and γ_ℓ is

a $M\times1$ matrix of channel gains for the ℓth TOA. A gradient of equation (24)

with respect to t_ℓ can be shown to be:

5

$$\nabla t_\ell = \sum_{k=0}^{K-1} \mathrm{Im}\left\{ ke^{jkt_\ell} \gamma_\ell^H \mathbf{H}_n(k) \right\} - \sum_{k=0}^{K-1} \mathrm{Im}\left\{ \sum_{\substack{p=1 \\ p\neq\ell}}^{P} \gamma_\ell^H \gamma_p k e^{-jk(t_p - t_\ell)} \right\}. \qquad (25)$$

Given the P TOA's, the gains $(P \times M)\gamma = [\gamma_1, \ldots, \gamma_P]^T$ may be found as

$$\gamma = \mathbf{R}^{-1}\mathbf{p} \quad \text{where} \quad \mathbf{R} = \sum_{k=0}^{K-1} \mathbf{f}(k)\mathbf{f}^H(k), \quad \mathbf{p} = \sum_{k=0}^{K-1} \mathbf{f}(k)\mathbf{H}^T(k), \quad \text{and} \quad \mathbf{f}(k) = \begin{bmatrix} e^{jkt_1} \\ \vdots \\ e^{jkt_P} \end{bmatrix}. \quad ($$

26)

Consequently, one embodiment of the invention may provide a

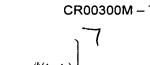10   gradient-based search for the TOA's as follows:

1. Start with P TOA's from an existing algorithm (e.g., ESPRIT or
the near-ML TOA algorithm).

2. Determine γ from equation (26).

3. Calculate ∇t_ℓ for $\ell=1,\ldots,P$ from equation (25), for $\ell=1,\ldots,P$, $t_\ell = t_\ell -$

15      $\alpha\nabla t_\ell$ where α is the step size.

4. If the stopping criteria are not reached, such as a maximum
number of iterations, then go to step 2.

FIG. 6 illustrates another embodiment of the invention using the

20   gradient-based search for TOA's. The gradient TOA channel estimation

method **600** may be provided a number, P, TOA estimates t_ℓ for $\ell=1\ldots P$, and

a step size α **610**. A noisy channel estimate may be determined as the

equation $\mathbf{H}_n(k) = \mathbf{Y}(k)/x(k)$. The TOA gradient for each TOA estimate may

next be calculated as a function of the TOA estimates and the noise channel

25   estimate **620**. The TOA gradient for the ℓth TOA, t_ℓ, can be shown as the

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equation $\nabla t_\ell = \sum_{k=0}^{K-1} \text{Im}\{ke^{jkt_\ell}\boldsymbol{\gamma}_\ell^H \mathbf{H}_n(k)\} - \sum_{k=0}^{K-1} \text{Im}\left\{\sum_{\substack{p=1 \\ p\neq\ell}}^{P} \boldsymbol{\gamma}_\ell^H \boldsymbol{\gamma}_p ke^{-jk(t_p-t_\ell)}\right\}$, where

$(P \times M)\boldsymbol{\gamma} = [\boldsymbol{\gamma}_1,...,\boldsymbol{\gamma}_P]^T$, and

$\boldsymbol{\gamma} = \mathbf{R}^{-1}\mathbf{p}$ where $\mathbf{R} = \sum_{k=0}^{K-1}\mathbf{f}(k)\mathbf{f}^H(k)$, $\mathbf{p} = \sum_{k=0}^{K-1}\mathbf{f}(k)\mathbf{H}^T(k)$, and $\mathbf{f}(k) = \begin{bmatrix} e^{jkt_1} \\ \vdots \\ e^{jkt_P} \end{bmatrix}$. The

TOA's can be updated for $\ell=1...P$ using $t_\ell=t_\ell-\alpha\nabla t_\ell$ where α is the step size

5   **630**. If a stopping criterion is not reached **640** such as a maximum number of
iterations is not reached, the iterations may continue from block **620**,
otherwise the algorithm may terminate **650**. The gradient search may not be
the preferred method to determine TOA's, but for one embodiment of the
invention, the gradient search may refine estimates that are reasonably close.

10   This is due to the objective function having many local minimums and that the
gradient search does not provide a good procedure for determining P and the
initial TOA's.

As is illustrated in **FIG. 7**, another adaptive channel estimation
embodiment of the invention can include an improved least squares channel

15   estimation method **700**. Assuming that there is only a single user, the least
squares (LS) channel estimator can parameterize a frequency-domain
channel as the weighted sum of L time taps, or equivalently the N-point DFT
of an L-tap time-domain channel as follows:

$$\mathbf{H}(k) = \sum_{\ell=0}^{L-1}\mathbf{h}(\ell)e^{-j2\pi k\ell/N} \qquad (27)$$

20   where N is the DFT size of the LS estimator (in OFDM, $N\geq K$). The LS
estimator for receive antenna m can be put in a matrix form as represented by
the equation:

$$\mathbf{h}_m = \begin{bmatrix} h_m(0) \\ \vdots \\ h_m(L-1) \end{bmatrix} = \mathbf{QY}_m \qquad (28)$$

where $\mathbf{Q}$ is $L \times K$ matrix that may provide a LS time-tap channel estimate as is known in the art, and $\mathbf{Y}_m$ is defined in the previous equation (4) with $U=1$.

In sparse channels the LS estimator can be improved by not estimating gains for taps below a certain power level, thus improving the pilot-to-

5   parameter ratio. In this embodiment of the invention, criteria may determine which taps are not estimated. Assuming that only white noise is present, the noise floor of the LS estimator can be represented by the equation:

$$\boldsymbol{\sigma}_h = \sigma_n \mathbf{Q} \mathbf{d} \tag{29}$$

where $\mathbf{d}$ is an $K \times 1$ vector of all ones.

10   The criteria within one embodiment of the invention for the removal of taps may be to remove all taps with power below $10 \log_{10}(\boldsymbol{\sigma}_h^H \boldsymbol{\sigma}_h) + 5\,\mathrm{dB}$. Once the taps are removed, the gains can be found using a LS procedure similar to equation (7). Using the described process, the least squares channel estimation method **700** may begin by being provided a time-domain channel

15   estimate for at least one user and a threshold value T **710**. In one embodiment of the invention, the threshold value may be represented by the equation $T = 10 \log_{10}(\boldsymbol{\sigma}_h^H \boldsymbol{\sigma}_h) + 5\,\mathrm{dB}$, where $\boldsymbol{\sigma}_h = \sigma_n \mathbf{Q} \mathbf{d}$, $\mathbf{d}$ is a $K \times 1$ vector of all ones, σ_n^2 is the noise power, and $\mathbf{Q}$ is a matrix that is known in the art which can provide a LS time-tap channel estimate. The time-domain channel

20   estimate may be provided from any existing channel estimator. In the Least Squares (LS) embodiment, the time-domain channel estimate on receive antenna m may be given as:

$$\mathbf{h}_m = \begin{bmatrix} h_m(0) \\ \vdots \\ h_m(L-1) \end{bmatrix} = \mathbf{Q}\mathbf{Y}_m, \text{ where}$$

$$(K \times 1) \quad \mathbf{Y}_m = \begin{bmatrix} Y_m(0) \\ \vdots \\ Y_m(K-1) \end{bmatrix} = \sum_{u=1}^{U} \mathbf{X}_u \mathbf{F}_u \boldsymbol{\gamma}_{m,u} + \mathbf{N}_m .$$ Any time-domain channel taps

25   whose magnitude is below the threshold value T, may be discarded by the invention in order to determine the dominant time-taps (time-taps values with power above the threshold value) **720**. In one embodiment of the invention,

the dominant time-taps may be the P time-taps labeled ℓ_1 through ℓ_P, and may represent ℓ for which $|h_m(\ell)|^2 > T$. With the dominant time-taps determined, the least squares channel estimation method **700** may re-estimate the channel for at least one user, only at the dominant time-tap (tap) values **730**. For the

5   previously described embodiment, the dominant tap values can be ℓ_1 through ℓ_P, whose gains (channel estimations) may be found using a LS procedure similar to equation (7), thus terminating **740** the least squares channel estimation method **700**

        The above-described methods and implementation of adaptive channel

10   estimation are example methods and implementations. These methods and implementations illustrate but one possible approach for adaptive channel estimation. The actual implementation may vary from the method discussed. Moreover, various other improvements and modifications to this invention may occur to those skilled in the art, and those improvements and modifications

15   will fall within the scope of this invention as set forth below.

        The present invention may be embodied in other specific forms without departing from its spirit or essential characteristics. The described embodiments are to be considered in all respects only as illustrative and not restrictive.

20